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Project ID/Title: INFLUENCE OF MACHINING PARAMETERS ON TOOL WEAR AND MACHINING PERFORMANCE IN HIGH SPEED DUCTILE MODE END MILLING OF SODA LIME GLASS

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Abstract:

Soda lime glass is used extensively in engineering application owing to its high hardness, excellent optical properties, and good corrosion and chemical resistance. Previous studies on ductile mode machining were conducted with the application of negative rake angle of the tool in order to achieve high hydrostatic pressure in the cutting zone to change the material from brittle to ductile state. In this research high speed end milling of glass in a conventional CNC were conducted in order to obtain ductile mode machining. Nevertheless, high speed machining (HSM) may increase the tool wear, especially for the carbide tools used in glass machining. Therefore on line heating of glass surface was carried out to reduce tool wear. In this research, the spindle speed was varied in the range 30000 to 50000 rpm, feed rate in the range 5 to 20 mm/min and depth of cut in the range 5 to 50 µm. The temperature of the soldering gun was maintained at 340°C. Mathematical models were developed for the output responses of average surface roughness (Ra) and tool wear for the two machining conditions, namely, without the application of heat and with the application of heat. It was found from the optimization that, minimum surface roughness and minimum tool wear in the experiment without heat assistance obtained at 41,000 rpm of spindle speed, feed rate of 7.12 mm/min and low depth of cut 5 µm. On the other hand, the suggested conditions for minimum surface roughness and tool wear in heat assisted machining were: spindle speed 38,000 rpm, feed rate 20 mm/min and depth of cut 50 µm. Comparing these two suggested optimum values it appears that the metal removal rate in heat assisted machining would be 26 times that of normal cutting to achieve similar surface roughness and tool wear values. This result shows that heat assisted machining will be more economical as the cost of the solder gun system and consumed electricity is very nominal.

Key words: *High speed machining, soda lime glass, tool flank wear, heat assisted machining, ductile mode machining*

Introduction:

Recently HSM is getting popular for the machining of brittle materials. The most advantageous feature of HSM is that with suitable selection of parameters it is possible to machine brittle material with high depth of cut and good surface finished. Ductile machining of brittle materials is facilitated by the heat softening phenomenon. This may be achieved in several ways, some achieved it in relatively low cutting speed machining through the application of negative rake angle, as negative rake angle increases the cutting force and develops high hydro-static pressure in the cutting zone thereby increasing the heat in the removable layer of the material (Sharma, Mahto, & Sen, 2013). This hike in temperature leads to softening of the material and brings it close to the glass transition temperature of the material and thus ductile removal of material is facilitated. However, in low speed machining the un-deformed chip thickness is quite low and does not facilitate economically viable option for brittle material machining. It has been also observed by some researchers that cutting temperature is the main factor which may affect the workpiece surface integrity, tool wear, and machining precision due to the relative motion between the tool and workpiece (Sayuti, Mohammed Sarhan, & Hamdi, 2010). The material and cutting parameters used especially, the cutting speed has high influence on the temperature generation during machining. The researchers also observed that high spindle speed produces heat that helps in the transition of brittle machining mode to ductile machining mode. Therefore, higher cutting temperature with high spindle speed helps in softening the material, reducing the cutting force and in achieving better surface finished. Tool wear is also reduced as a result of lower cutting forces. Nevertheless, researchers concluded that in high speed machining the spindle speed should be at an optimum value, excessively high cutting speeds might lead to high temperature and resulting in poor surface finish and higher tool wear. Thus optimization of cutting and external heating temperature in high speed machining of soda lime glass is crucial in achieving desired value of surface roughness and minimum possible tool wear values.

The work of Amin, & Musa (2011) on high speed ductile mode machining of Single Crystal Silicon demonstrated that the heat developed during the process of cutting was sufficient to bring the material layers to ductile mode machining. The current work planned to go one step further, to try to increase the un-deformed chip thickness further through application of online heating to the work material. It was expected that, during machining, high temperature generated due to the combined application of the cutting process generated heat and the externally applied heat would be higher and would facilitated the achievement of ductile mode machining involving higher material removal rate. This would be helpful in arriving at economically viable method of ductile material machining.

Background:

Soda lime glass is used extensively in camera lens, micro gas turbines, light bulbs, tableware, optics, and chemical apparatus owing to its high hardness, excellent optical properties, and good corrosion and chemical resistance. Such applications demand high precision and therefore, machining of soda lime glass is very essential in many industrial applications. However, machining of glass poses significant challenges due to its inherent brittleness. The process of removing material can generate subsurface cracks in soda lime glass and compromise its functionality. One solution to this problem is high speed ductile regime machining which enables material removal from brittle material in a ductile manner rather than by fracture. However, certain condition and parameters must be strictly maintained in order to achieve ductile mode machining of soda lime glass. Previous studies have detailed the use of high hydrostatic pressure and large negative rake angles in the cutting inserts to accomplish ductile regime machining, especially in end milling operations. In contrast, this research will use a more economical approach: the high speed end milling of glass in a conventional CNC end mill in order to obtain ductile machining. The idea is that high cutting speeds produce high temperatures on account of increased friction, which can approach the glass transition temperature of soda lime glass. At these temperatures the glass behaves in a ductile manner, thereby obviating the need for expensive techniques and negative rake angles. However, high speed machining (HSM) causes increased tool wear, especially for the carbide tools used in glass machining. Therefore, this research will specifically investigate the influence of the three primary cutting parameters: spindle speed, feed rate, and axial depth of cut on tool wear. Also high speed machining of soda lime glass accompanied by online heating of the work material is carried out to reduce tool wear and at the same time getting improve surface finish and material removal rate

Objectives: This research will investigate the influence of the cutting parameters during ductile mode machining of soda lime glass on tool wear and try to determine the optimum combination of these parameters for minimizing the wear. Therefore, the main objective of this project is to model tool wear and minimize it by optimizing the cutting parameters. The specific objectives of this research are:

1. To identify the value of the cutting parameters (Spindle Speed, Feed Rate, and Depth of Cut) that will lead to ductile mode machining and reduced tool wear.
2. To develop empirical mathematical model of surface roughness and tool wear in terms of the machining parameters: cutting speed, feed, and axial depth of cut using Response Surface Methodology (RSM) and to identify the effect of the cutting parameters on tool wear.
3. Finally, to optimize the surface roughness and tool wear and also determine the most suitable combination of cutting parameters.

Methodology:

The widely used brittle material, soda lime glass was chosen as workpiece material in this research work. The tools used for this study was 2-flute 4 mm carbide flat end mill.

Three main cutting parameters considered were spindle speed, depth of cut and feed rate. The response considered for the model development were Average Surface roughness (R_a) and tool wear (flank wear). All the experiments were conducted on the CNC milling machine which is very convenient to be used and easy to be conducted. An ultra-precision high speed milling attachment Nakanishi HES510 capable of up to 50,000 rpm and 250W output-with compressed air was used to achieve high rotational speed per minute during end-milling operation. The experimental works were carried with aid of soldering system in order to add heat onto the surface machined. The solder kit from heating system will be attached besides the tool in order to increase the temperature during experiment and achieved ductile mode machining. A Kistler Ceramic Shear Accelerometer Type 8774A50 will be used for sensing and acquiring the vibration data in observing ductile regime machining.

The response of average surface roughness was measured in the non-contact optical profiler Wyko NT1100. Flank wear response was measured by using NK measuring instrument. The experimental runs were designed based on the three level full factorial design concept of Response Surface Methodology (RSM). The function of three level full factorials is to ensure that all machining condition is run to the fullest for the experimentation. The experimental run will be generated by the Design Expert 6.0.8 software from a range of cutting parameter which will be determine from the studies of literature review as mention earlier.

Design-Expert 6.0.8 software was used to analyze the measured roughness and tool wear results in order to develop a predictive model. Lastly, the developed RSM models of average surface roughness as well as tool wear were utilized to optimize the cutting parameters and compared with the addition of heat.

Experimental Setup

Experimental of high speed end milling of soda lime glass under two different conditions, namely, without and with the application of online heating were conducted. The soldering systems were used in order to add heat onto the surface machined as shown in Figure 1. The diameter of solder tip 4 diameter was selected which is the same diameter with the tool. It is due to have a focus heat applied onto the surface machined. The solder system can control heat up to 480°C using control unit. However, moderate constant heat 340°C applied in the experiment

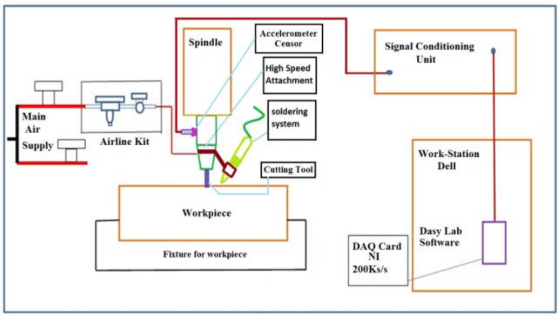

Figure 1. Block Diagram of experimental setup of heat assisted high speed end milling of soda lime glass.

Experimental Results:

Experimental results of surface roughness in high speed end milling of soda lime without and with the application of heat are shown in Table 1.

Table 1 The Experimental results of surface roughness

Std	Run	Factor 1	Factor 2	Factor 3	Response 1	Response 1
		A:Spindle Speed (RPM)	B:Feed Rate (mm/min)	C:Depth of Cut, (µm)	Surface Roughness (µm)	Surface Roughness (µm)
					Without Heat	With Heat (340 °C)
1	1	40	12.5	3	0.27	0.23
3	2	30	20	5	0.82	0.31
9	3	40	12.5	27.5	0.51	0.19
5	4	40	12.5	27.5	0.39	0.17
7	5	50	5	50	0.23	0.24

13	6	30	12.5	27.5	0.21	0.20
11	7	40	3	27.5	0.25	0.39
15	8	50	12.5	27.5	0.38	0.41
17	9	40	12.5	65.34	0.64	
16	10	50	5	5	0.25	0.31
12	11	50	20	5	0.53	0.48
14	12	30	20	50	1.04	0.32
2	13	50	20	50		0.49
4	14	30	5	5	0.17	0.32
10	15	40	25.11	27.5	0.98	0.27
6	16	40	12.5	27.5	0.24	0.21
8	17	30	5	50	0.27	0.21

The effect of spindle speed on value of surface roughness response is in Figure 3 shows that surface roughness obtained from end milling of soda lime glass with heat reduces to a minimum value and then increases when the spindle comes to the highest level 50 000 rpm.

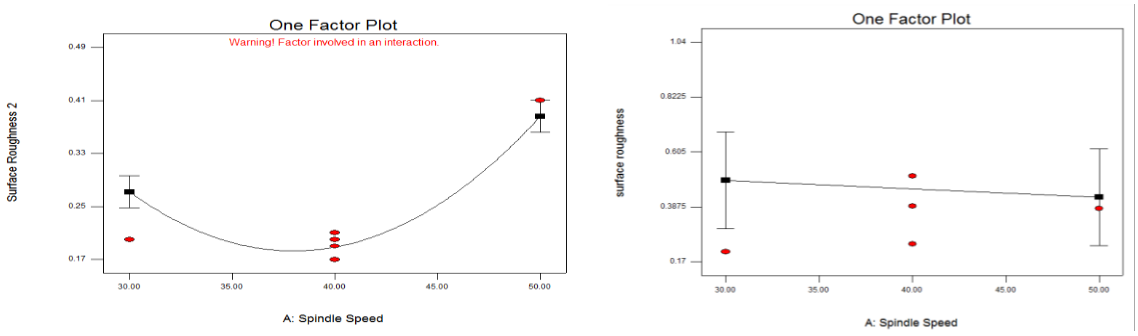

Figure 2 surface roughness vs. spindle speed, (a) without heat (b) with heat.

The effect of feed rate on value of surface roughness response is illustrated by figure 3 shows the same type of graph when the surface roughness increase when the feed rate increase.

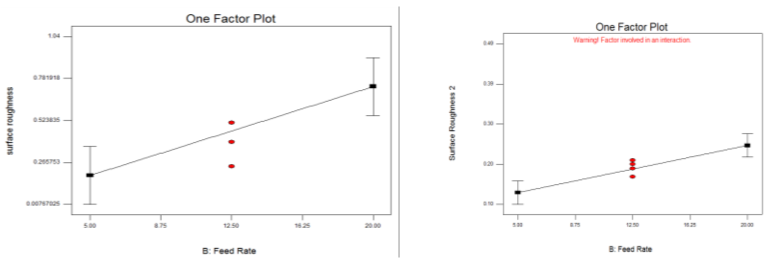

Figure 3 surface roughness vs. Feed rate, (a) without heat (b) with heat

Similarly the surface roughness value decreases by the increasing of depth of cut in case of heat assisted experiment

The empirical model developed by RSM analysis is given in Equation 1 and 2. x_1 , x_2 *and* x_3 represents rpm, feed rate and depth of cut respectively.

Average surface roughness (without heat)

- R_a= 0.027349004 - 0.003319233 x_1 + 0.036454244 x_2 + 0.003952089 x_3………. (1)

Average surface roughness (with heat)

- R_a= 1.085945288 - 0.013325397 x_1 - 0.050082589 x_2 - 0.006750441 x_3 - 0.002127976 x_4 + 0.000583333 x_1 x_2 - 1.11111E-05 x_1 x_3 + 3.48214E-05 x_1 x_4 + 0.000362963 x_2 x_3 + 6.66667E-05 x_2 x_4 + 1.23016E-05 x_3 x_4 …. (2)

Experimental results of flank wear in high speed end milling of soda lime glass using 4 mm carbide end milling tools without application of heat is shown in Table 2

Table 2 Experimental results of flank wear

Std	Run	Factor 1 A:Spindle Speed (RPM)	Factor 2 B:Feed Rate (mm/min)	Factor 3 C:Depth of Cut, (µm)	Response 2 Flank Wear (µm)	Response 2 Flank Wear (µm)
					Without Heat	With Heat (340 °C)
1	1	40	12.5	3	42.048	45.552
3	2	30	20	5	50.808	44.676
9	3	40	12.5	27.5	34.42	43.800
5	4	40	12.5	27.5	123.516	42.924
7	5	50	5	50	61.32	45.552
13	6	30	12.5	27.5	45.552	48.180
11	7	40	3	27.5	56.064	63.072
15	8	50	12.5	27.5	57.816	82.344
17	9	40	12.5	65.34	57.816	
16	10	50	5	5	59.568	46.428
12	11	50	20	5	84.972	48.180
14	12	30	20	50	59.568	39.420
2	13	50	20	50	131.4	31.336
4	14	30	5	5	55.188	45.552
10	15	40	25.11	27.5	97.236	36.792
6	16	40	12.5	27.5	59.568	44.676
8	17	30	5	50	50.808	50.088

The effect of spindle speed on value of flank wear response is illustrated by Figure 4 Shows that application of heat cause the flank wear to reduce at highest level of speed 50 000rpm.

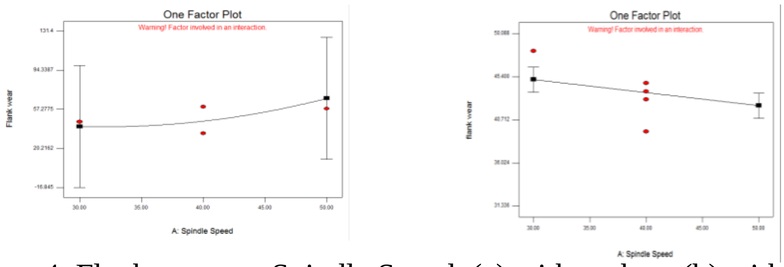

Figure4. Flank wear vs. Spindle Speed, (a) without heat (b) with heat.

According to the Figure 5, Flank wear result obtained from the experiment without heat show the increasing of flank wear by the increasing of feed rate..

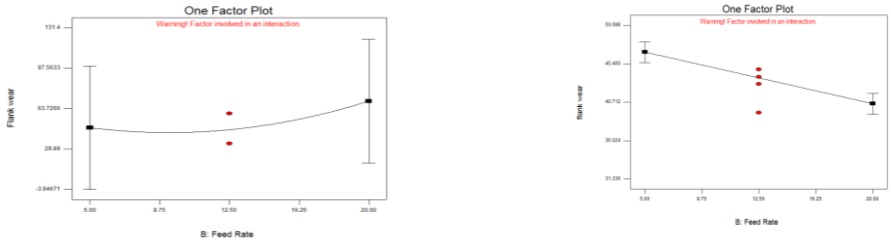

Figure 5 Flank wear vs. Feed Rate, (a) without heat (b) with heat.

Similarly without the application of heat show that flank wear value increases slightly with the increase in depth of cut. However, the surface roughness value decreases visibly by the increasing of depth of cut for the experiment that applied heat.

The empirical model of flank wear developed by RSM analysis is given in Equation 2 and 3.

Flank wear (without heat):

- Flank Wear = 253.8252923 - 7.823073057 x_1 - 11.47011417 x_2 - 1.391235751 x_3 + 0.08234283 x_1^2 + 0.22808985 x_2^2 + 0.002702961 x_3^2 + 0.15184 x_1 x_2 + 0.024333333 x_1 x_3 + 0.042826667 x_2 $x3$ ……………………………………………………….(2)

Flank wear (with heat):

- Flank Wear = 39.59188531 + 0.137202576 x_1 + 0.166513366 x_2 + 0.51715059 x_3 - 0.001533333 x_1x_2 - 0.009444444 x_1x_3 - 0.019081481 x_2x_3 ……………… (3)

At the numerical optimization section, desirability function approach of DOE has been used to identify the minimum value of average surface roughness response and minimum tool wear response. Table 3 shows the optimization results.

Table: 3 optimization results

	Spindle Speed (Rpm)	Feed Rate (mm/min)	Depth of Cut (µm)	Surface Roughness (µm)	Tool Wear (µm)	Desirability
Heat (340 °C)	38.74	20.00	50.00	0.24	35.518	0.781893
Without Heat	41.18	7.12	5.00	0.169995	45.3683	0.941864

Conclusion:

1. The models developed for R_a and tool wear by RSM for soda lime glass surface using DOE was found to be able to provide a reliable prediction of the values of responses within a confidence level of more than 80%. Thus, the models could be used if applied within the ranges listed in experimental conditions
2. According to the surface roughness models developed, it was found that for achieving good surface finish in machining without heat application combination of low spindle speed, low feed rate and low depth of cut is essential, whereas for achievement of the same effects in heat assisted machining combination of high spindle speed, high feed rate and high depth of cut is preferred.
   - Machining with no heat give surface roughness value which was 0.39 µm at spindle speed 40 000 rpm, feed rate of 12.5 mm/min and 27.5 µm of depth of cut. Machining under heat assisted give lowest surface roughness which was 0.17 µm under the same parameters.
   - Low tool wear can be obtained by increasing all parameters when the heat applied during machining. Compared to glass machining with no heat, lower parameters needed in order to get minimum tool wear.
   - At 50 000 rpm, feed rate 20 mm/min and 50 µm of depth of cut shows highest tool wear during machining without heat which was 131.4 µm. However, tool wear achieved down to 31.336 µm when machining during heat assisted.
3. From the optimization results it is found that the metal removal rate in heat assisted high speed end milling of soda lime glass could be as high as 28 times approximately for the achievement of similar surface roughness
4. On the other hand, tool wear optimization result shows that feed rate give main individual effect on tool wear followed by spindle speed and depth of cut. Then, tool

wear that obtained from the experiment with the existence of heat tells that depth of cut provide a strong individual effect on tool wear followed by spindle speed and feed rate.

5. Response optimization by desirability function of RSM show 94% desirability for minimum attainable combinations of average surface roughness (Ra) and tool wear under end milling of soda lime glass using 4 mm carbide tool without the application of heat and 78% under the application of heat. The desirable value present that the model can be accepted for other machining under the range of cutting parameters material.

Output:

1. AKM Amin, AA Omar, M Kamal, M Nassar, NF Mohd Zaib, MD Arif. (2015). Achievement of Ductile Regime Machining in High Speed End Milling of Soda Lime Glass by Using Tungsten Carbide Tool Insert, J. Advanced Materials Research 1115, pp. 39-42.
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Future Plan of the research:

Future research work in high speed machining of soda lime glass could be taken up in the following areas:

i. Experiments could be done considering cutting parameters in wider ranges, varying the tool geometry and application of different tools, such as ball mill, torus end mill, etc.
ii. In future study, other efficient technique can be proposed in applying the machining with heat in which it may give a constant heat onto the surface machined.
iii. Additional study could be done on other glass material like crown glass, pyrex glass and even ceramic material.
iv. Future study can be taken up for more surface integrity tests like residual stress, change of micro structure after machining, micro hardness test, etc.
v. Cutting force could be considered as one of the response parameter in the future work as it is also an important parameter for glass machining.

vi. The finite element analysis can also be used to simulate the effects end milling of glass to observe the stress distribution and strain rate for optimization of cutting process.

vii. Fuzzy logic, Artificial Neural Network (ANN) and other prediction modeling techniques can be examined for model development.

viii. Glass machining economic analysis can be considered as it may minimize the production cost in mass production industry.

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